Fin whale vocalizations observed with ocean bottom seismometers of cabled observatories off east Japan Pacific Ocean

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Fin whale vocalizations were found in the archived waveform data from both hydrophones and ocean bottom seismometers (OBSs) of a cabled observatory off Kushiro-Tokachi in Hokkaido. A fin whale was localized on the basis of the incident orientation estimated with a single OBS and the time difference of multipath arrival of sound pressure data from a hydrophone. Furthermore, several fin whale vocalizations were found in the archived OBS waveform data from other cabled observatories off east Japan Pacific Ocean. These findings suggest that the cabled OBSs would be significant apparatuses for real-time monitoring of the presence of baleen whales around Japan.

A fin whale, one of the large baleen whales, is known to exist worldwide and to vocalize low-frequency sounds at 17 – 25 Hz[1]. The possibility that some of the baleen whales communicate with each other using deep sound channels to transmit their low-frequency sounds in the vast ocean has been pointed out and some simulation studies have been tried to verify such a possibility[2,3]. Numerous previous studies of vocal features and the ecology of baleen whales based on passive acoustic observations of their vocalizations have been carried out in detail in the Atlantic Ocean, North and East Pacific Ocean, and the Arctic regions using temporary or permanent underwater observatories or hydrophone arrays, as shown in Refs. 2, 4, and 5, for example. However, in the West Pacific Ocean, especially around Japan, few such passive observations have been carried out because there are only a few apparatuses that can be used for scientific underwater acoustic observations. Recently, fin whale vocalizations have been found in the sound pressure data obtained with hydrophones attached to the ocean bottom seismometers (OBSs) of the cabled observatory off Kushiro-Tokachi in Hokkaido Prefecture in Japan[6-8]. On the other hand, fin whale vocalizations were also found in the archived waveform data obtained with the OBSs. Although presently there are only a few underwater acoustic apparatuses suitable for monitoring whale vocalizations around Japan, there are a moderate number of cabled OBSs; moreover, a large number of seafloor seismic observatories are being constructed or are planned to be constructed for the purpose of mitigating earthquake and/or tsunami disasters[9,10]. If those cabled OBSs are confirmed to be capable of detecting the whale vocalizations, they would become bimodal apparatuses for detecting seismic activities and whale vocalizing features, leading to their greater understanding. Consequently, the cabled system may also contribute to the understanding of the ecology of whales around Japan, which is less known than that in other parts of Pacific region. In this study, firstly the waveform data from OBSs on the fin whale vocalizations observed at the observatory off Kushiro-Tokachi were surveyed and the localization of the sound source, i.e., the fin whale, was attempted. Secondly, the waveform data from OBSs at other cabled seismic observatories deployed in the east Japan Pacific Ocean region were examined and the “excavation” of the fin whale vocalizations was attempted.

The off Kushiro-Tokachi cabled observatory has four hydrophones and three OBSs. Three of the four hydrophones are attached to three OBSs (OBS1, OBS2, and OBS3 in Fig. 1). The remaining hydrophone is attached to the cable-end observatory, which consists of multidisciplinary sensors such as a conductivity, temperature, and depth of water (CTD) sensor, an acoustic doppler current profiler (ADCP), and a video camera. The sampling rate of all data continuously obtained with the hydrophones and the OBSs is 100 Hz.

An OBS is composed of three accelerometers that are placed perpendicular to one another in a cylindrical pressure chassis. Both edges of the chassis are connected to the submarine cable. The X-axis of the OBS is parallel to the cylindrical axis and accordingly to the cable. The Y- and Z-axes are perpendicular to the cable; however, their inclination is arbitrary on the seafloor; that is, they are not completely vertical nor horizontal. To obtain data on geographical coordinates (north-south, east-west, up-down), raw data (X, Y, and Z) must be converted on the basis of the direction of gravity derived from the offsets of acceleration in raw data and the absolute orientation of the X-axis, which is confirmed by observation with a remotely operated vehicle on the seafloor. The method of conversion is described in Ref. 11.

Sample spectrograms of fin whale vocalizations observed with the hydrophone and the Z-component of the OBS at OBS1 at the same time (from 14:00 to 15:00 JST on Dec. 10th, 2004) are shown in Figs. 2 and 3, respectively. The vocalization signals in both figures have similar frequencies in the range of 15–20 Hz and at a duration of about 1 s, which are typical features of fin whale vocalizations[7)].

In previous studies, fin whales were localized by a seismic network composed of several OBSs, whose horizontal intervals were 3–5 km in Northeast Pacific Ocean or in Northeast Atlantic Ocean[12.13)]. In Ref. 12, the localization of a whale is carried out using the difference in the arrival time of the vocalization signals at several OBSs by ray tracing. At the off Kushiro-Tokachi observatory, the horizontal intervals of OBSs are 40–60 km, sparser than those reported in Ref. 12, and the vocalization signals arrived only at one OBS. Consequently, this method described in Ref. 12 is not considered in this study. In Ref. 13, a whale was localized using the estimated incident angle and incident orientation of the vocalization signal measured by an OBS. The estimation of the incident angle on the seafloor, which was used for the estimation of the horizontal range between the OBS and the whale, is affected by the density and P-wave (pressure wave) velocity of both sediments and water, and is also affected by the SV-wave (share wave) velocity of the sediments. In Ref. 13, the consistency of those estimations was verified to some extent using air gun signals generated at known positions. However, in this study, many of those parameters were unknown; thus, the horizontal range was estimated from the time difference of multipath arrival (TDOMA) of sound pressure data obtained with the hydrophone[14)], with the following assumptions. (1) The sound source (i.e., a fin whale) was at the sea surface. (2) The sound velocity was constant. (3) The water depth was constant.

A special case of the setting described in Ref. 14 is that the depth of the receiver is equal to the water depth and that the depth of the sound source is zero.

TDOMA can be calculated by Eq. (1), where *r*, *d*, and *V* are the horizontal range, water depth, and sound velocity in water, respectively:

$$TDOMA = \frac{\sqrt{r^2+9d^2}}{V} - \frac{\sqrt{r^2+d^2}}{V} \ . \qquad (1)$$

Figure 4 explains the derivation of Eq. (1). A multipath includes the reflections at both the seafloor and sea surface. By placing a virtual mirror source, which is commonly used for the reflective acoustic boundary as described in Ref. 15, the travel time of the multipath signal becomes equal to the travel time between the receiver (hydrophone) and the mirror source.

Figure 5 shows the relationship between the TDOMA and the horizontal range. The sound velocity in water is assumed to be 1500 m/s. The water depths are 2329 m for OBS1 (solid curve) and 2540 m for the cable-end observatory (dashed curve), which are the water depths of the corresponding sites. The difference in the curve implies an error level of about 1 km for the same TDOMA concerning the assumption of a constant water depth.

Figure 6 shows an example of the horizontal particle motion (left) and 10 s band-pass-filtered (10–25 Hz) waveforms observed with hydrophones and the OBS at 14:09:13 on Dec. 10th, 2004 JST. On the right side of Fig. 6, the waveforms from the hydrophone at the cable-end observatory, the hydrophone at OBS1, and the vertical, north-south, and east-west components of the OBS at OBS1 are shown from top. The left and right arrows indicate the direct and multipath arrival times of the hydrophone signal at OBS1, respectively. The horizontal particle motion was drawn from the 1 s waveform at the direct arrival time of the horizontal components of the OBS waveform on the right side of the figure. The incident orientation of the particle motion was estimated by principal component analysis and by obtaining the eigen vector of the first main component[16]. On the basis of the relationship between the TDOMA and the horizontal range in Fig. 5, according to the TDOMA of the hydrophone signal and the incident orientation at OBS1 in Fig. 6 and two more results of the successive observations at 14:41:15 and 14:59:23, a fin whale was localized, as shown in Fig. 7, which suggests that it was moving towards south-south-west near the east of OBS1.

Besides the observatory off Kushiro-Tokachi, there are several seismic underwater cabled observatories consisting of OBSs, some with tsunami pressure gauges, which are deployed around Japan for the purpose of monitoring submarine earthquakes and tsunamis. The sampling rates of the OBS data of these observatories are usually 100 Hz, the same as those of the observatory off Kushiro-Tokachi. The author examined part of the archived OBS waveform data obtained at three of those observatories located in the east Japan Pacific Ocean area - observatories off Kamaishi and off Boso, and the Sagami Bay observatory. The locations of these observatories are shown in Fig. 8. As a result, several fin whale vocalizations were detected at all of these observatories. An example of the spectrogram of those vocalizations observed at the observatory off Kamaishi is shown in Fig. 9. At the observatory off Boso and the Sagami Bay observatory, the vocalizations were detected from 00:00 to 01:00 JST on Jan. 10th, 2005 and from 05:00 to 06:00 JST on Apr. 16th, 2006, respectively.

Although in this study several examples of fin whale vocalizations have been found to date in only a limited period, it is confirmed that the existing cabled OBSs have the capability to detect fin whale vocalizations. Since the first deployment of the cabled seismic observatory off Tokai in 1978[17)], there has been a long history of continuous observation of earthquakes in the ocean in Japan. Moreover, a large number of other cabled OBSs are being constructed or are planned to be constructed in the near future. They would become significant apparatuses not only for monitoring and mitigating earthquake and/or tsunami disaster but also for long-term real-time continuous monitoring of the large baleen whales around Japan, where presently there is a lack of acoustic data indicating the presence of the baleen whales.

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Figure Captions

Fig. 1. Location of OBSs and a cable-end observatory of cabled observatory off Kushiro-Tokachi in Hokkaido.

Fig. 2. (Color online) Spectrogram of fin whale vocalizations observed with hydrophone at OBS1 from 14:00 to 15:00 JST on Dec. 10th, 2004.

Fig. 3. (Color online) Spectrogram of fin whale vocalizations observed with Z-component of OBS at OBS1 from 14:00 to 15:00 JST on Dec. 10th, 2004.

Fig. 4. Schematics of multipath and virtual mirror source.

Fig. 5. Relationship between TDOMA and horizontal range.

Fig. 6. Horizontal particle motion (left) and 10 s band-pass-filtered (10–25 Hz) waveforms of fin whale vocalizations (right) observed with hydrophones and OBS at 14:09:13 on Dec. 10th, 2004 JST. From top, waveforms of the hydrophone at the cable-end observatory, the hydrophone at OBS1, and vertical, north-south, and east-west components of the OBS at OBS1 are shown. The left and right arrows indicate the direct and multipath arrival times of the hydrophone signal at OBS1, respectively.

Fig. 7. Localized position of a fin whale.

Fig. 8. Locations of the cabled seismic observatories examined in this study. (a) observatory off Kushiro-Tokachi, (b) observatory off Kamaishi, (c) observatory off Boso, and (d) Sagami Bay observatory.

Fig. 9. (Color online) Spectrogram of fin whale vocalizations observed with Z-component of the OBS at OBS1 of cabled observatory off Kamaishi from 17:00 to 18:00 (JST) on Feb. 27th, 2005.

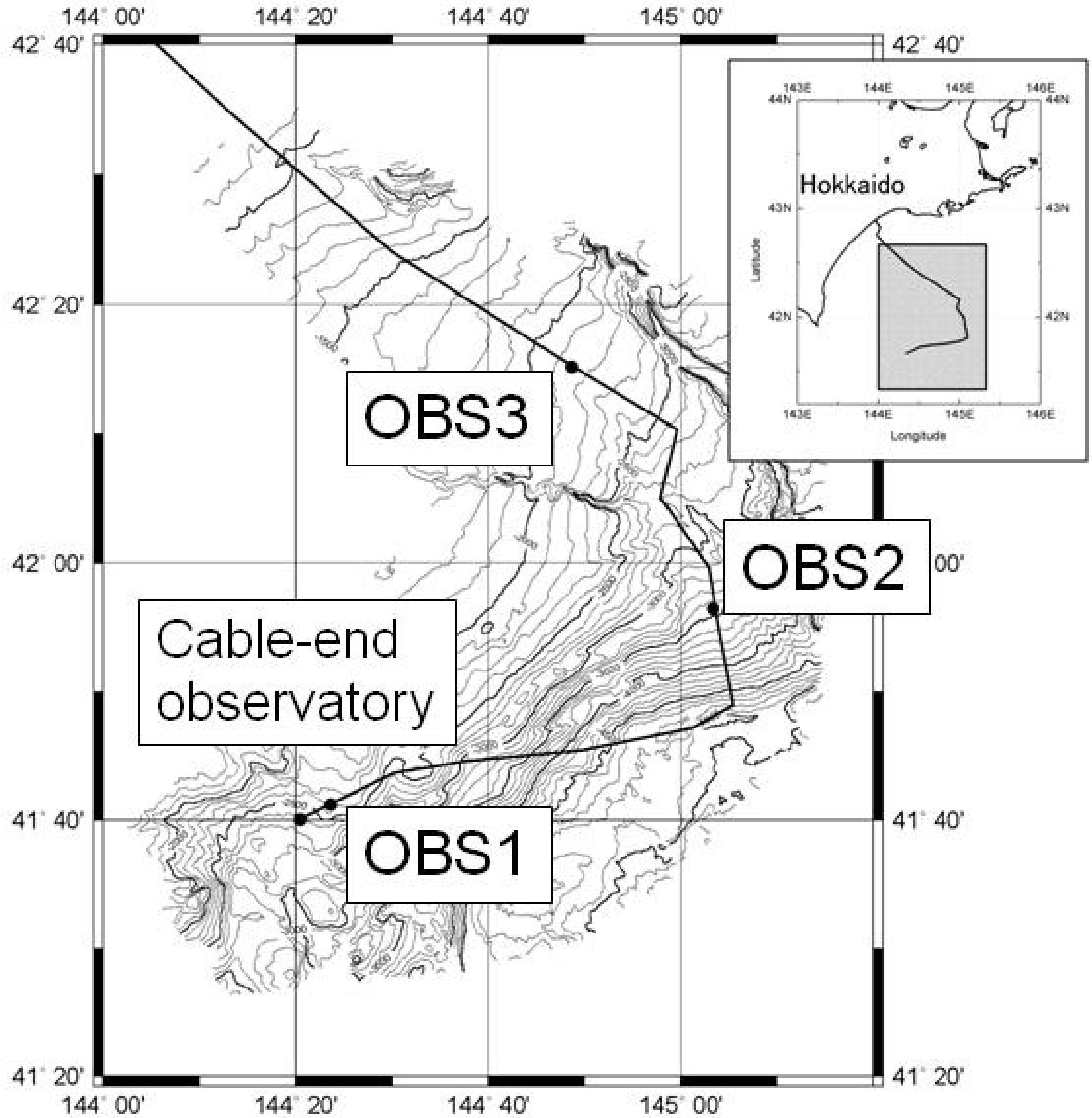

144° 00'
144° 20'
144° 40'
145° 00'
42° 40'
42° 20'
42° 00'
41° 40'
41° 20'
OBS3
OBS2
Cable-end observatory
OBS1
Hokkaido
Latitude
Longitude
143E
144E
145E
146E
44N
43N
42N

Fig. 1.

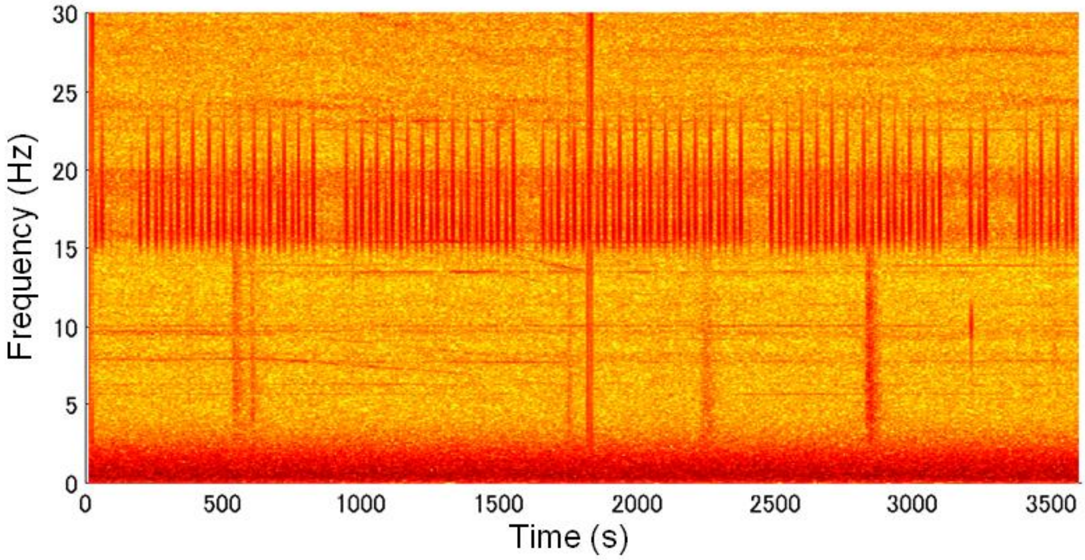
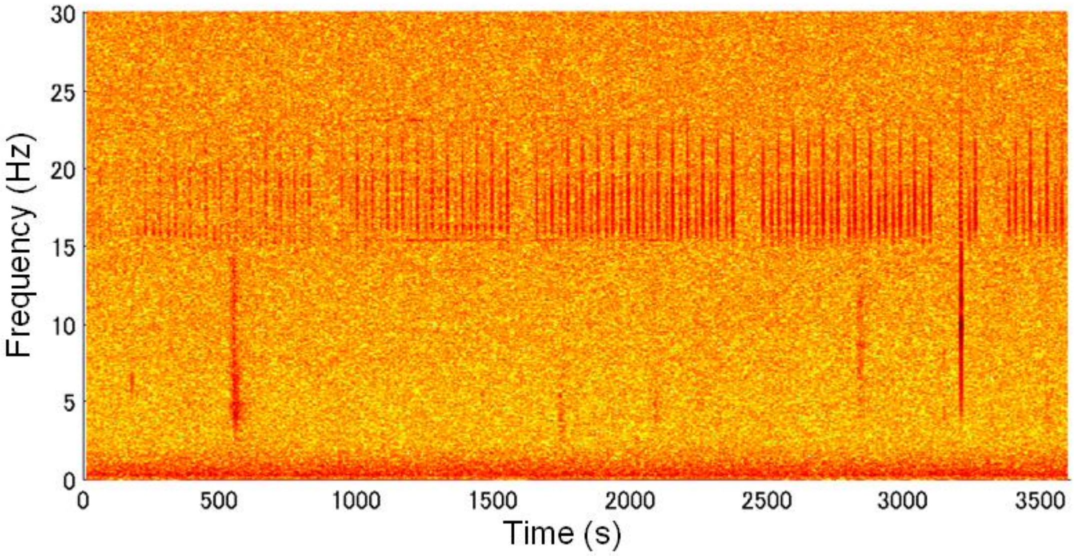


Fig. 2. (Color Online)



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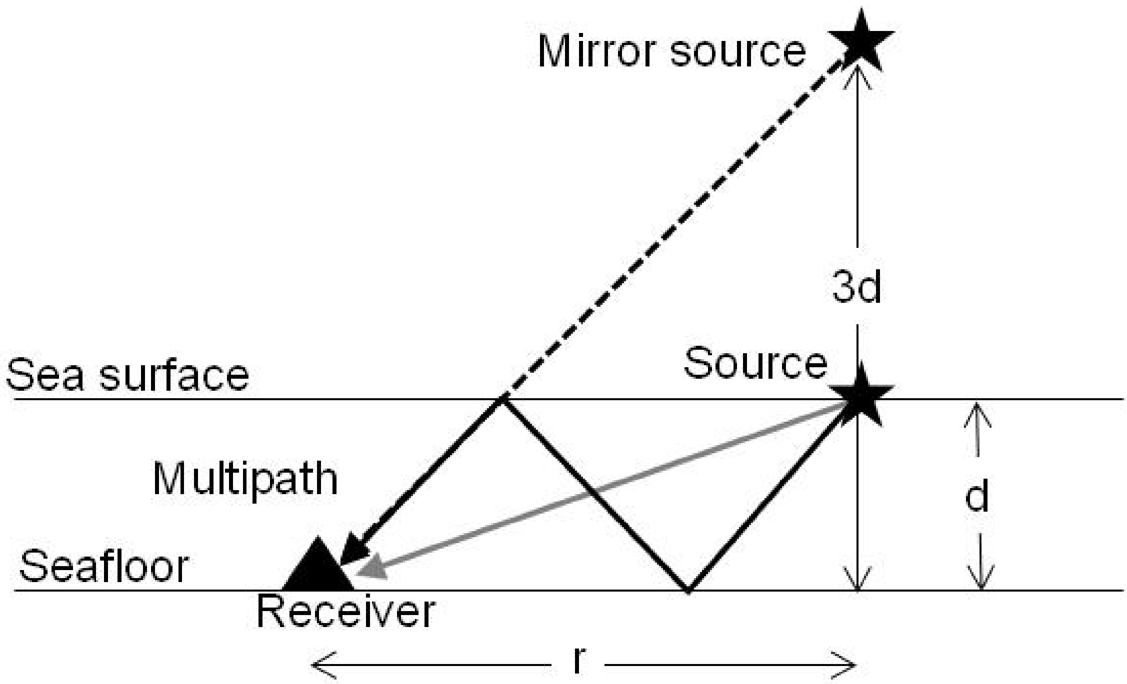
Mirror source
3d
Sea surface
Source
Multipath
d
Seafloor
Receiver
r

Fig. 4.

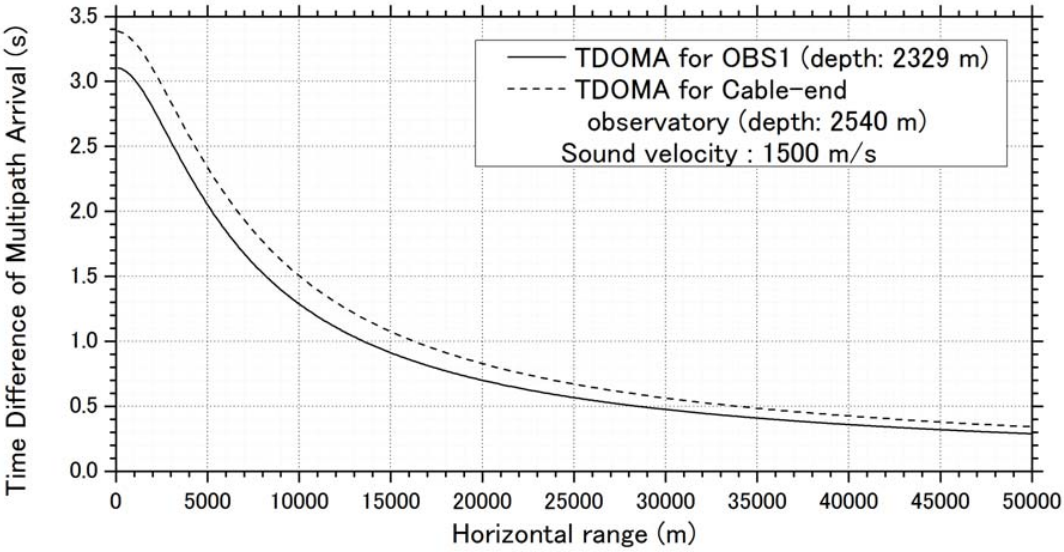
TDOMA for OBS1 (depth: 2329 m)
TDOMA for Cable-end observatory (depth: 2540 m)
Sound velocity : 1500 m/s
Time Difference of Multipath Arrival (s)
Horizontal range (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000

Fig. 5.

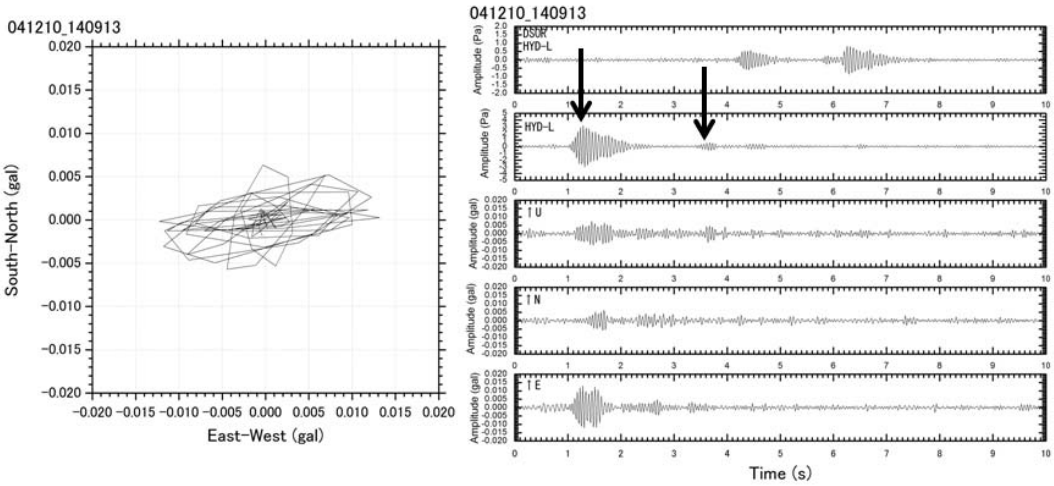
041210_140913
South-North (gal)
East-West (gal)
041210_140913
DSUR
HYD-L
HYD-L
Amplitude (Pa)
Amplitude (gal)
TU
TN
TE
Time (s)

Fig. 6.

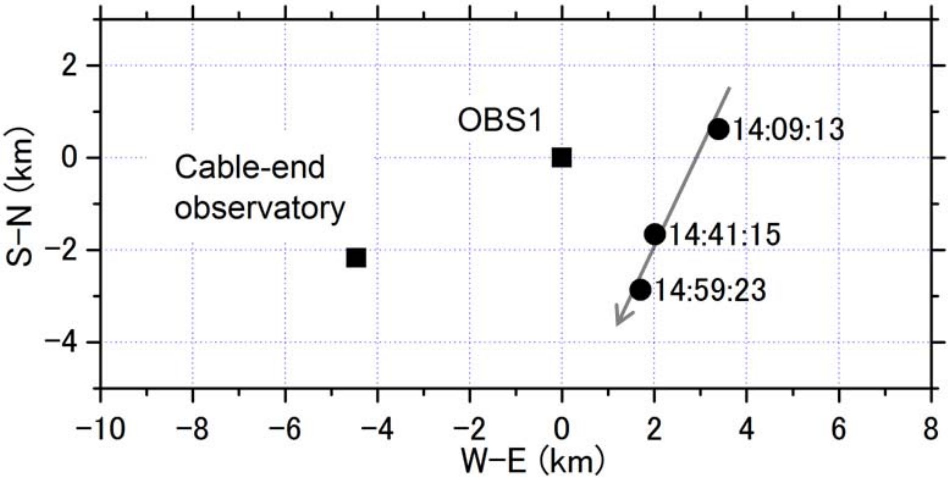
OBS1
Cable-end
observatory
14:09:13
14:41:15
14:59:23
S−N (km)
W−E (km)
2
0
−2
−4
−10
−8
−6
−4
−2
0
2
4
6
8

Fig. 7.

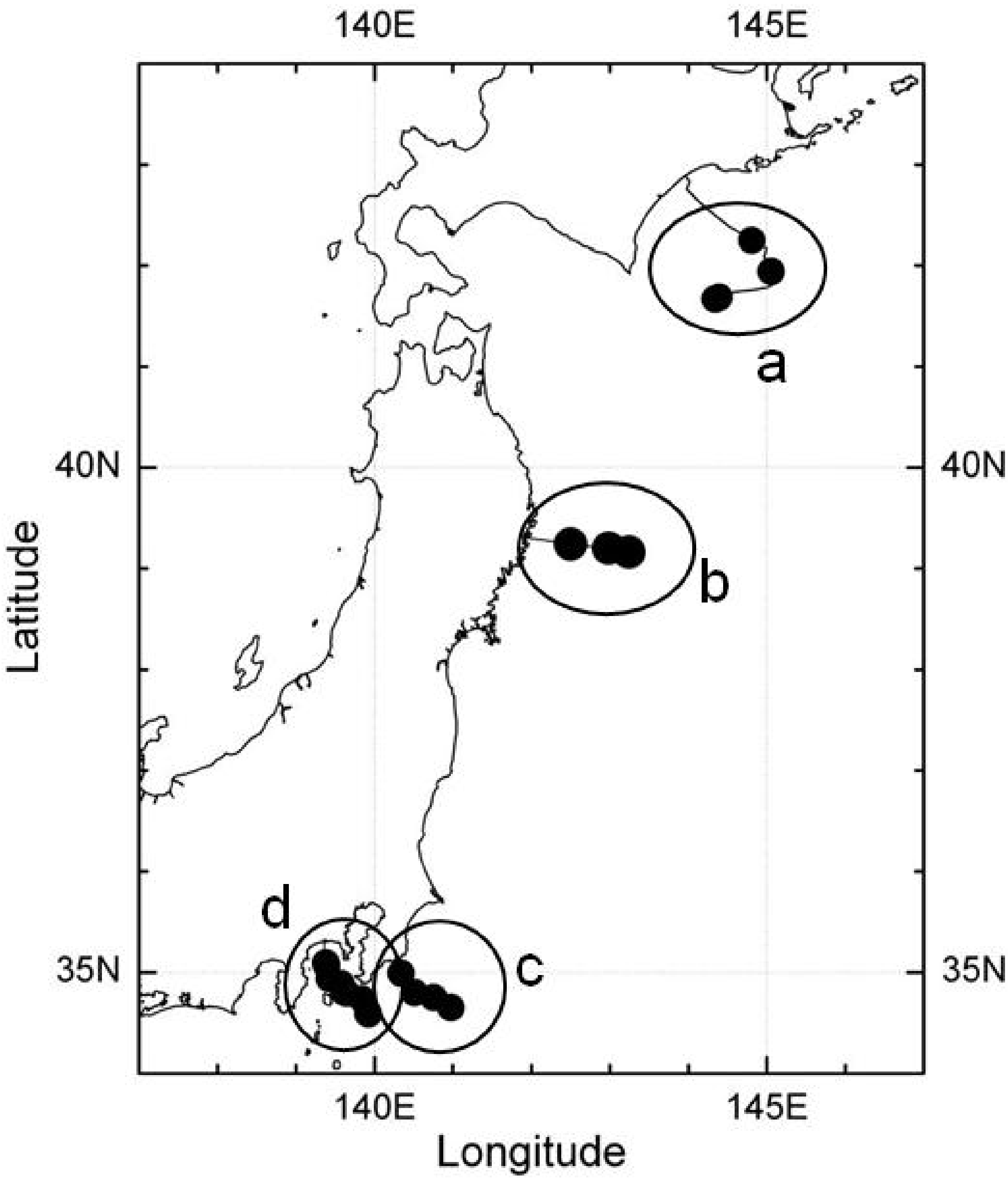

Fig. 8.

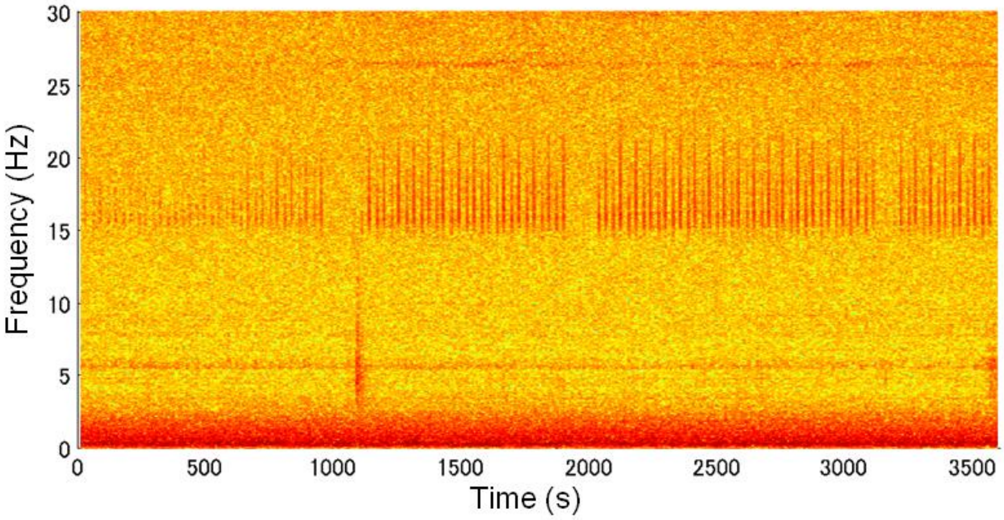

Fig. 9. (Color Online)